



Resistive vibration exercise during bed-rest reduces motor control changes in the lumbo-pelvic musculature

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ABSTRACT

To understand the effects of a resistive vibration exercise (RVE) countermeasure on changes in lumbo-pelvic muscle motor control during prolonged bed-rest, 20 male subjects took part in the Berlin Bed-Rest Study (in 2003–2005) and were randomised to a RVE group or an inactive control group. Surface electromyographic signals recorded from five superficial lumbo-pelvic muscles during a repetitive knee movement task. The task, which required stabilisation of the lumbo-pelvic region, was performed at multiple movement speeds and at multiple time points during and after bed-rest. After excluding effects that could be attributed to increases in subcutaneous fat changes and improvements in movement skill, we found that the RVE intervention ameliorated the generalised increases in activity ratios between movement speeds ($p \leq 0.012$), reductions in lumbo-pelvic extensor and flexor co-contraction ($p = 0.058$) and increases in root-mean-square electromyographic amplitude ($p = 0.001$) of the lumbar erector spinae muscles. Effects of RVE on preventing increases in amplitude-modulation ($p = 0.23$) of the lumbar erector spinae muscles were not significant. Few significant changes in activation-timing were seen. The RVE intervention during bed-rest, with indirect loading of the spine during exercise, was capable of reducing some, but not all, motor control changes in the lumbo-pelvic musculature during and after bed-rest.

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1. Introduction

Bed-rest represents a unique model of extreme musculoskeletal disuse, particularly of the lower quadrant (Booth and Gollnick, 1983). The methodology of prolonged bed-rest was originally developed to act as a simulation of the effects of spaceflight on the human body (Nicogossian and Dietlein, 1982). An additional aim of space agencies in implementing bed-rest studies is to better understand the effect of “inactivity” on the human body and in so doing aiming to improve our management of illness on Earth. Specifically in the musculature, the muscle groups most affected by bed-rest are those involved in upright posture and locomotion, such as the triceps surae, vasti and lumbar spine extensors (Belavý et al., 2011, 2009b). In recent works, we have attempted to gain a better understanding of the effects of bed-rest on motor control at the lumbo-pelvic region (Belavý et al., 2010, 2007a,b). Some of the

findings have included development of generalised overactivity in the superficial lumbo-pelvic muscles, more phasic activation of the lumbar erector spinae and shift to higher median activation frequencies in this same muscle.

However, aside from gaining a better understanding of the effects of bed-rest on the human body, another goal of bed-rest studies is the development of countermeasures against the changes seen in spaceflight simulation. This information will help not only in the development of (exercise) programmes for preventing musculoskeletal deterioration in spaceflight, but may also better insight into treatment regimes on Earth for deconditioned patients. In the Berlin Bed-Rest Study (Armbrecht et al., 2010; Rittweger et al., 2006), a high-load resistive exercise programme with whole-body vibration (RVE) was implemented. This exercise programme was targeted predominately at the bones (Armbrecht et al., 2010; Rittweger et al., 2010) and muscles (Belavý et al., 2009c; Blottner et al., 2006; Mulder et al., 2006) of the lower limbs. Nonetheless, indirect loading of the lumbar spine occurred via shoulder straps. Magnetic resonance imaging investigations in these same subjects showed that the RVE subjects exhibited less atrophy of the short lumbar spine extensor muscles than in the

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control subjects (Belavý et al., 2008). Hence, we hypothesised that the RVE countermeasure would ameliorate the extent of motor control changes, as measured by electromyography, seen in the lumbo-pelvic muscles of the inactive control subjects.

2. Materials and methods

2.1. Bed-rest protocol

The “Berlin Bed-Rest Study” was implemented by the Centre of Muscle and Bone Research at the Charité Benjamin Franklin Hospital in Berlin, Germany, from February 2003 to May 2005. Twenty male subjects underwent 8 weeks of strict bed-rest with a subsequent 6-month follow-up recovery period. The bed-rest protocol, as well as inclusion and exclusion criteria, is discussed in detail elsewhere (Rittweger et al., 2006). In brief, subjects were randomly allocated to either a group that remained inactive (controls, CTRL) or a group that underwent a whole-body resistive vibration exercise countermeasure programme (RVE group) using the Galileo Space exercise device (Novotec Medical, Pforzheim, Germany). Subjects were required to remain in bed at all times. Subjects were also requested to restrict movement in bed to the minimal required for hygiene and other necessary daily tasks. Adherence to this protocol was monitored by continuous video recordings and by use of force transducers in the frame of the bed. The institutional ethics committee approved this study and subjects gave their informed written consent. After bed-rest, all subjects were offered a generalised (cardiovascular fitness and strength) rehabilitation programme at a local physiotherapy practice and returned to their normal work and leisure activities.

2.2. Countermeasure exercise

RVE subjects underwent two exercise sessions daily (morning and afternoon) of approximately 5–10 min each during bed-rest. A detailed description of the exercise protocol has been published elsewhere (Armbrecht et al., 2010; Rittweger et al., 2006). In brief, whilst in supine position, subjects placed their feet on a suspended vibrating platform. An axial force was placed through the subjects' trunk and spine via elastic shoulder straps. The loading levels applied through the shoulder straps depended upon the exercise manoeuvre performed and the stage of exercise load progression during the study (see Armbrecht et al., 2010; Rittweger et al., 2006 for further detail) and ranged from 1.2 to 1.8 times body weight. A belt was also attached around the pelvis and hand-grips attached to the frame from which the vibrating platform was suspended. Morning and afternoon exercise sessions were performed. The exercises performed were: squats (from 90° of knee flexion to near full extension), heel raises (with the knees in near extension, heels raised into ankle plantarflexion) and toe raises (with the knees in near extension, forefoot raised into ankle dorsiflexion) against the platform. Each exercise was performed for more than 60 s. In morning sessions, subjects also performed 10 repetitions of “explosive kicks” (explosive pushes against the vibrating platform from near full knee and hip flexion) at intervals of 10 s. The vibration depended upon exercise manoeuvre performed and the stage of exercise progression but ranged from 19 to 26 Hz. However, for each training session the frequency was constant for the duration of each exercise. Vibration frequency was increased if the subject could perform an exercise for more than 100 s. Vibration amplitude was held constant at 4 mm. During afternoon sessions, subjects exercised at only 60–80% of the static force used in the morning sessions and the exercises were performed continuously until exhaustion.

2.3. Repetitive knee movement model and testing protocol

The knee movement and lumbo-pelvic muscle loading model has been described in prior publications (Belavý et al., 2010, 2007a,b). In brief, to allow the examination of motor control parameters in the lumbo-pelvic musculature during isometric activation, a model using repetitive knee movement to stimulate cyclic modulation of isometric lumbo-pelvic muscular activity was conducted. The movement paradigm was implemented using repetitive right knee movement in prone lying. Straps were placed over the subject's buttocks and distal thigh to reduce movement at these points and expedite isometric lumbo-pelvic muscle action. Movement was conducted with the right leg and a spring was attached to the right ankle to counteract the gravitational weight of the lower leg (Richardson and Bullock, 1986; Richardson, 1987). This experimental setup thus permitted standardised loading of the lumbo-pelvic musculature both during and after bed-rest.

Subjects conducted right knee flexion and extension between 0° and 45° of knee flexion at four movement speeds (50, 75, 100 and 125 cycles per minute [cyc/min]). Three repetitions of 11 s were conducted at each movement speed. During each repetition, subjects paused their breathing to remove the influence of respiration on lumbo-pelvic muscle activity (Hodges and Gandevia, 2000). Subjects were able to view a feedback monitor through a cut out in the support apparatus. An electrogoniometer was placed at the right knee to provide data on knee position. Baseline data was collected on the first day of bed-rest (BR1). Subsequent testing occurred on the 4th, 13th, 27th, 41st and 53rd days of bed-rest (BR4, BR13, BR27, BR41 and BR53) and on the 3rd, 7th 14th, 28th, 90th, 180th and 360th day of “recovery” (R+) post-bed-rest (R + 3, R + 7, R + 14, R + 28, R + 90, R + 180, R + 360).

2.4. Lumbo-pelvic muscle EMG and signal acquisition

Five superficial lumbo-pelvic muscles were monitored. To examine different functional parts of the erector spinae with surface EMG, electrodes were placed over the lumbar erector spinae with multifidus (LES; at the level of the 5th lumbar vertebrae between the spinous process and a line drawn from the posterior superior iliac spine to the interspace between the 1st and 2nd lumbar vertebrae (de Foa et al., 1989; Ng et al., 2001) and thoracic erector spinae (TES; at the level of the 2nd and 3rd lumbar interspace, 1 cm medial to a line drawn from posterior superior iliac spine to the lateral border of the erector spinae at the 12th rib (de Foa et al., 1989; Ng et al., 2001). Surface EMG using these placements has been shown to correlate highly with intra-muscular electrodes in the underlying muscles during a range of manoeuvres (Arokoski et al., 1999) and electrodes placed at least 3 cm apart over different parts of the erector spinae, as in the current work, can be regarded as giving sufficiently specific signals (Vink et al., 1989). The abdominal muscles were monitored with electrodes placed over the internal oblique (IO; the superior electrode placed 1 cm medial to the anterior superior iliac spine, the inferior electrode placed parallel to the inguinal ligament at the standard inter-electrode distance (Ng et al., 1998; Ng et al., 2001)) and external oblique (EO; at the most inferior point of the costal margin orientated along a line from that point to the contralateral pubic tubercle (Ng et al., 1998; Ng et al., 2001)). The inferior portion of the gluteus maximus muscle (IGM), which has a different function to the more cranial portion (Lyons et al., 1983), was monitored with electrodes placed inferior and medial to a line drawn between the posterior superior iliac spine and posterior greater trochanter (Lyons et al., 1983). Bipolar Ag/AgCl surface electrodes were placed at an inter-electrode distance of 35 mm. Using the placements utilised in the current work, prior

work has been able to distinguish functional differences in muscle activation in the different parts of the erector spinae and abdominal obliques (Lyons et al., 1983; Ng et al., 2001, 2002). Electrodes were also placed over the right biceps femoris muscle to monitor leg muscle activity at rest. A ground electrode was placed at the right elbow. Standardised skin preparation was performed involving washing the skin, shaving and the application of an abrasive-conductive gel.

EMG and goniometer data were sampled simultaneously at 2000 Hz using a Powerlab system running Chart version 4.2 software (AD Instruments, Sydney, Australia) with a 16 bit A/D converter, band-pass filtered from 15 to 500 Hz and were stored for offline processing. During testing, subjects were given real-time visual feedback on movement speed and position. A second computer also sampled the goniometer signal and implemented custom written software in the Labview environment (version 6.1, National Instruments, Texas) to provide this feedback.

2.5. Goniometer signal processing and movement accuracy

Prior to processing EMG data, the goniometer signal, which was sampled simultaneously with the EMG signals, was first processed to select data “regions” which fulfilled the following criteria: beginning at a minima nearest 0°, three consecutive movement cycles during which each movement cycle’s speed was within ± 5 cyc/min of the target speed, and the maxima (near 45°) and minima (near 0°) were within $\pm 4^\circ$ of their respective targets. This process was conducted to limit the effect of extremes of performance on the observed motor control patterns and further standardise the experiment. This processing also provided information on movement accuracy for correlation analyses: mean-squared-error (*MSE*) of movement speed (*MSE_{speed}*), maxima positions (*MSE_{45°}*) and minima positions (*MSE_{0°}*). These *MSE* values were calculated for each data region. In addition, the *MSE* of movement speed (*All-MSE_{speed}*), maxima positions (*All-MSE_{45°}*) and minima positions (*All-MSE_{0°}*) were calculated for the entire goniometer signal from each trial. This additional movement accuracy data was then used to track changes in movement performance over the course of the study. As we focus here on the motor control changes in bed-rest, data on movement accuracy have been included in online [Supplementary](#) material). Unless otherwise stated all algorithms here, were implemented in the Labview environment (version 6.1, National Instruments, Texas).

2.6. EMG signal processing

The EMG signal processing method is described in [Fig. 1](#). EMG data were band-pass filtered from 20 to 500 Hz using a 10th order digital Butterworth filter. Then, in each selected data “region” the corresponding EMG signal was extracted and the root-mean-square (*RMS*) activation level was computed. In addition to this, the following variables were calculated:

- *Ratio*: the calculation of EMG amplitude “ratios” between experimental conditions have been used previously to examine the effects of different movement protocols (Hodges and Gandevia, 2000) and have been shown to reduce inter-subject variability (Winter and Yack, 1987). As it was inappropriate, and difficult practically in the horizontal position, to perform maximal voluntary contractions repeatedly during a strict bed-rest study, the use of amplitude-ratios between movement speeds helps to avoid some of the difficulties associated with measuring raw EMG amplitude (such as due to subcutaneous fat; Nordander et al., 2003). In the current work, we calculated three “activity-ratios” (*ratio_{75/50}*, *ratio_{100/75}*, *ratio_{125/100}*) for each muscle by dividing each *RMS* value from movement speeds 75

cyc/min and above by the median *RMS* value of the speed below. This variable could be considered a measure of the degree to which the central nervous system “ramps” the activity-levels of each muscle with increases in movement speed.

- *CoCon*: abdominal flexor-lumbar extensor antagonistic co-contraction (*CoCon*) was quantified using an “area-normalisation” method adapted from prior work (Vinther et al., 2005; Winter, 2004). The following algorithm was used:
 - Generation of a “linear-envelope” from the entire 11 s EMG signals of the EO, IO, LES and TES muscles by high-pass filtering at 100 Hz using a digital 10th order quasi-Butterworth filter, rectification, and then low-pass filtering using a 10 Hz digital 10th order Bessel filter.
 - Partitioning of the linear-envelope into the appropriate data region (as determined from goniometer signal analysis).
 - Normalisation of the area of each linear-envelope region to “1” by dividing each value by the total area under the curve.
 - The greater value of the LES and TES signals was taken at each data point and the resulting signal was re-normalised as in step [c] (generating an “extensor linear-envelope”).
 - The abdominal IO and EO signals were processed in the same fashion as in steps [b], [c] and [d] to yield a “flexor linear-envelope”.
 - The area of overlap of the flexor and extensor linear-envelopes was calculated and this value ranged from 0 to 1 and represented the lumbo-pelvic flexor and extensor co-contraction variable (*CoCon*).
- *BTR*: or “burst-to-tonic ratio” examined the degree of amplitude-modulation present in the EMG signal. This measurement aimed to quantify the extent of a phasic “burst” of electromyographic activity superimposed on the ongoing, or “tonic”, activity during the movement cycle (Belavý et al., 2009a,b). Since the muscles were typically continuously active during the movement task, the following algorithm was used:
 - Generation of a “linear-envelope” from the entire 11 s EMG signal of every muscle (as in step [a] of *CoCon* calculation: 100 Hz high-pass, 10th order digital Butterworth filter, followed by full-wave rectification, and then low pass filtering using a 10 Hz, 10th order digital Bessel filter).
 - Partitioning of the linear-envelope into the appropriate data region (as per step [b] of *CoCon* calculation).
 - Detection of maxima and minima of the linear-envelope using quadratic least-squares fit.
 - Calculation of median maximum and median minimum values.
 - Calculation of the ratio of the median maximum to minimum values, giving the “burst-tonic-ratio” (*BTR*) representing the relative height of the phasic burst component to the underlying ongoing tonic EMG activity. Thus, *BTR* values approaching “1” indicate more tonic muscle activation.

Due to the number of parameters examined, we focus on the *ratio*, *CoCon* and *BTR* variables in the current publication as these variables, in our view, are most functionally relevant and resistant to extraneous factors, such as subcutaneous fat. However, for the interested reader, we include in online [Supplementary](#) material the data on the *RMS* variables. We also examined the timing of muscle activity using an algorithm implemented in previous works (Belavý et al., 2010; Belavý et al., 2006). These latter data have been presented in online [Supplementary](#) data for the interested reader.

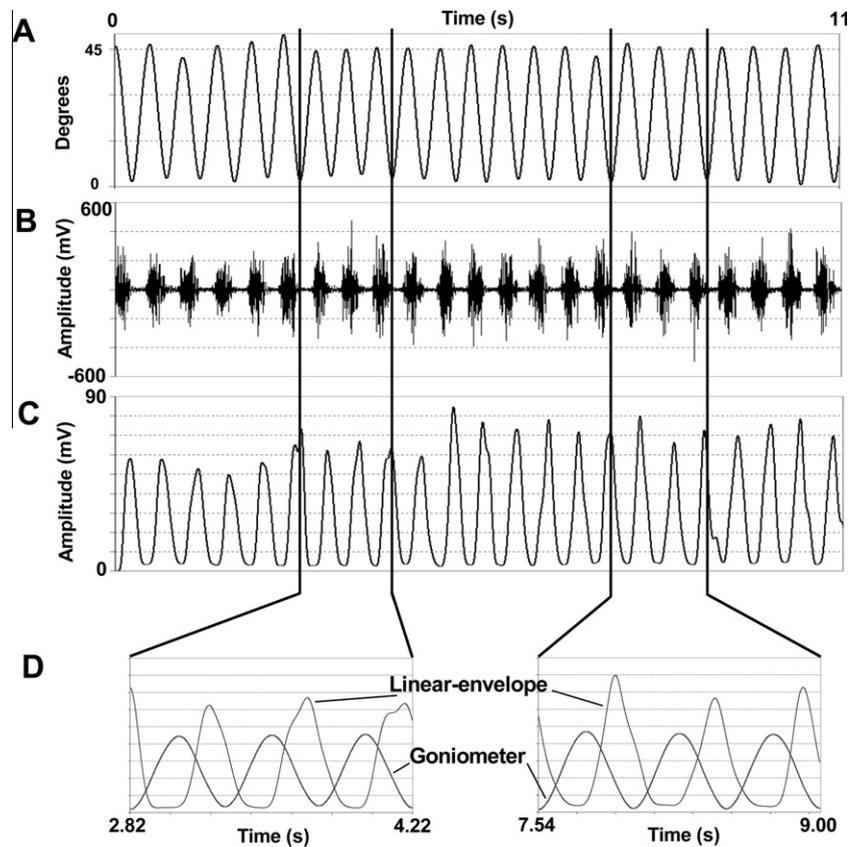


Fig. 1. Electromyographic signal processing and parameter measurement. (A) Goniometer signal from a movement-trial at 125 cyc/min. Of the total of five “regions” (three consecutive movement cycles) of the goniometer signal found to be of sufficient accuracy (see text for details), two regions are marked by the vertical lines. Measurements on the goniometer signal at this stage also provided movement accuracy data. (B) Corresponding EMG signal from the lumbar erector spinae after band-pass filtering (Butterworth) from 20 to 500 Hz. The root-mean-square (RMS) was calculated from the EMG signal within each data region at this stage. The RMS data was also used to calculate EMG amplitude “activity-ratios” (*ratio*) between movement speeds. (C) The entire EMG signal was high-pass (Butterworth) filtered at 100 Hz, full-wave rectified, and low-pass filtered (Bessel) at 10 Hz to produce the linear-envelope. (D) Maxima and minima are detected in the linear-envelope subsections using a detection algorithm to enable calculation of amplitude-modulation (*BTR*). The movement frequency is determined from the goniometer signal sub-section from its amplitude spectrum. At this movement frequency, the phase-value (in radians) in the phase spectrum of the EMG linear-envelope sub-section is subtracted from the corresponding value of the goniometer signal sub-section phase spectrum. This generates the phase-lead/lag (*PHZ*) measurement. To determine lumbo-pelvic flexor and extensor co-contraction (*CoCon*), the area of overlap between the linear-envelope signals from the abdomen and spinal extensors was calculated. See text for further details on signal processing. Data on PHZ and RMS have been presented in online Supplementary material for the interested reader and are not discussed in detail here.

2.7. Body composition data

A Delphi W (Hologic, Waltham, MA) system was used to perform total body scans according to the standard Hologic Operator’s Manual 3-days prior to bed-rest (BDC-3), on day BR2, BR17, BR31, BR45 and BR55 of the bed-rest phase and on R + 14, R + 28, R + 90, R + 180 and R + 360 during recovery phase. Fat mass (in kilograms) of the trunk (from pelvis to shoulders) were derived from the whole-body scan. All scanning and analyses were performed by the same operator to ensure consistency and standard quality control procedures were followed. BDC-3 and BR2 data were averaged prior to provide a more precise baseline measure.

2.8. Further data processing and statistical analyses

The natural-logarithm of the *ratio* and *BTR* variables was calculated prior to further analysis in order to approximate a near-normal distribution of the residuals. For the EMG variables *ratio* and *BTR* linear mixed-effects models (Pinheiro, 2000) were used to fit fixed effects for “group”, “muscle”, “study-date”, “movement speed” and all interactions up to a four-way interaction between these variables. For the *CoCon* and *All-MSE* variables similar models were constructed but without the factor of “muscle”. Similarly, for

trunk fat mass, factors of “group”, “study-date” and their two-way interaction were included in the calculation. Differences between the groups at baseline were also evaluated in a similar fashion, but without the “study-date” term. Allowances for heterogeneity of variance were made due to “group”, “muscle”, “study-date” and/or “movement speed” where necessary. Depending on the results from analysis of variance (ANOVA), subsequent modelling was performed as appropriate, such as between groups within each muscle or within movement speeds to determine which level of a given factor was responsible for an effect. Subsequently, the changes within each group compared to baseline were calculated. An α of 0.05 was taken for statistical significance on ANOVA. As multiple measurement sessions were undertaken on the same subjects, we examined for consistent significant differences across testing days. Correlation (Pearson) analyses, using the baseline data alone, were also performed between the movement accuracy and EMG variables and also between trunk fat mass and EMG variables (presented in online Supplementary material). For the movement accuracy and EMG variables, partial (Pearson) correlation analyses, controlling for muscle and movement speed, were also performed (online Supplementary material). The “R” statistical environment (version 2.10.1, www.r-project.org) was used to implement analyses.

3. Results

Due to subject absence or technical difficulties, not all data from each subject on every scheduled testing day were available. The numbers of subjects able to be included in statistical analysis on each testing day are given in online [Supplementary material](#).

3.1. Baseline data and correlation analyses

Data from the first day of bed-rest (BR1) are presented in [Tables 1 and 2](#). There were no differences between the groups at baseline ([Tables 1 and 2](#)). Correlations amongst movement accuracy and electromyographic variables as well as partial correlations (controlling for muscle and movement speed) are presented in online [Supplementary material](#). When the influence of muscle and movement speed are not controlled for, a number of low to moderate correlations exist between movement accuracy and EMG variables and also between each of the EMG variables. The partial correlations (online [Supplementary material](#)) show, however, that there was little relation between the movement accuracy variables and the EMG parameters. However, some moderate correlations between EMG parameters persisted.

3.2. Movement accuracy

Performance of the movement task, as measured by mean-squared-error of the goniometer signal maxima (around the 45° target; $All-MSE_{45^\circ}$) and minima (around the 0° target; $All-MSE_{0^\circ}$) as well as movement speed ($All-MSE_{speed}$) typically improved over the course of the study (online [Supplementary material](#)). This effect was strongest in the $All-MSE_{45^\circ}$ and $All-MSE_{speed}$ variables with reductions in both of these variables seen in both groups (online [Supplementary material](#)). The improvements in movement performance did not differ between the RVE and CTRL groups for $All-MSE_{45^\circ}$ or $All-MSE_{speed}$ ($p \geq 0.09$). For $All-MSE_{0^\circ}$ there was some evidence of a different response between the two groups (group \times study-date \times movement speed: $p = 0.006$), though further ANOVAs at each movement speed suggested a difference between the groups at the 75 cyc/min movement speed only ($p = 0.045$;

Table 1

Baseline (BR1) flexor–extensor co-contraction.

Movement speed	CoCon	
	Inactive control group (CTRL)	Resistive vibration exercise group (RVE)
50 cyc/min	0.91(0.02)	0.92(0.02)
75 cyc/min	0.88(0.02)*	0.86(0.02)*
100 cyc/min	0.82(0.02)‡	0.77(0.02)‡
125 cyc/min	0.80(0.02)‡	0.73(0.03)‡

CoCon variable (lumbo-pelvic extensor and flexor co-contraction) does not have a unit. * $p < 0.05$. † $p < 0.01$. ‡ $p < 0.001$ and indicates significance of difference to value at 50 cyc/min. Reductions in the CoCon variable imply less overlap between extensor and flexor muscle activity and hence less co-contraction. There were no differences between the groups at baseline ($p = 0.072$).

otherwise $p \geq 0.10$). At this 75 cyc/min speed, no significant effects changes compared to baseline were seen in either group and there was no clear pattern of difference between the two groups (data not shown).

3.3. Electromyographic variables

For the *ratio* variable, significant group \times study-date ($p = 0.011$) and group \times study-date \times movement speed ($p = 0.012$) effects were seen on ANOVA, with otherwise no significant differences between muscles over time ($p \geq 0.58$). Pooled across all movement speeds, increases in amplitude-ratios were seen in the CTRL group, with decreases in the RVE group ([Fig. 2](#)). When examining the ratio data at each movement speed ([Fig. 3](#)), the increased activity-ratios were seen in the CTRL group at the highest speeds ($ratio_{125/100}$), whereas RVE group shows little change at highest movement speeds, but reduction of $ratio_{75/50}$ over the course of study. The different responses of the two groups were significant for $ratio_{75/50}$ ($p = 0.0068$) and $ratio_{125/100}$ ($p = 0.0036$) but not for $ratio_{100/75}$ ($p = 0.26$).

Lumbo-pelvic extensor and flexor co-contraction (CoCon) decreased in the CTRL group with typically non-significant increases in the RVE group ([Fig. 2](#)). The difference between the groups did not however reach significance on ANOVA (group \times study-date:

Table 2

Baseline (BR1) electromyographic parameters.

Movement speed (cyc/min)	Muscle				
	External oblique	Inferior gluteus maximus	Internal oblique	Lumbar erector spinae	Thoracic erector spinae
<i>Amplitude-ratio (no unit) – inactive control group (CTRL)</i>					
75	1.26(0.13)	1.37(0.21)	1.57(0.21)	2.40(0.54)	1.27(0.17)
100	1.65(0.17)	1.80(0.28)	1.83(0.25)	2.15(0.48)	1.54(0.21)
125	1.69(0.20)	1.88(0.31)	1.43(0.21)	1.59(0.38)	1.61(0.24)
<i>Amplitude-ratio (no unit) – resistive vibration exercise group (RVE)</i>					
75	1.17(0.14)	1.26(0.07)	1.62(0.17)	4.14(0.57)	1.29(0.14)
100	1.50(0.18)	1.51(0.09)	1.77(0.18)	2.81(0.38)	2.30(0.25)‡
125	1.58(0.23)	1.82(0.14)†	1.67(0.21)	1.65(0.28)†	1.65(0.21)
<i>Amplitude-modulation (BTR; no unit) – inactive control group (CTRL)</i>					
50	1.46(0.13)	1.34(0.15)	1.55(0.07)	1.45(0.33)	1.39(0.12)
75	1.60(0.15)	1.70(0.19)	1.62(0.08)	2.53(0.57)*	1.56(0.14)
100	1.79(0.17)	2.33(0.26)‡	1.75(0.08)†	5.47(1.24)‡	2.01(0.19)†
125	2.55(0.26)‡	2.90(0.35)‡	1.98(0.10)‡	6.23(1.49)‡	2.38(0.24)‡
<i>Amplitude-modulation (BTR; no unit) – resistive vibration exercise group (RVE)</i>					
50	1.44(0.05)	1.29(0.09)	1.51(0.14)	1.30(0.26)	1.34(0.13)
75	1.45(0.05)	1.59(0.12)*	1.60(0.15)	3.53(0.74)†	1.54(0.15)
100	1.59(0.06)*	2.05(0.15)‡	1.89(0.17)*	8.06(1.66)‡	2.30(0.23)†
125	1.80(0.09)†	2.34(0.21)‡	2.00(0.22)*	14.43(3.50)‡	2.59(0.33)‡

Values are mean(SEM) amplitude-ratio (*ratio* between RMS values at 75 and 50 cyc/min, 100 and 75 cyc/min and 125 and 100 cyc/min), amplitude-modulation (burst-to-tonic ratio, BTR; a ratio of EMG signal height peak and trough measurements after signal processing). * $p < 0.05$. † $p < 0.01$. ‡ $p < 0.001$ and indicates significance of difference to value at 75 cyc/min for amplitude-ratio and to value at 50 cyc/min for amplitude-modulation. There were no significant differences between the groups at baseline ($p \geq 0.096$). See [Table 1](#) for baseline values of lumbo-pelvic extensor and flexor co-contraction (CoCon).

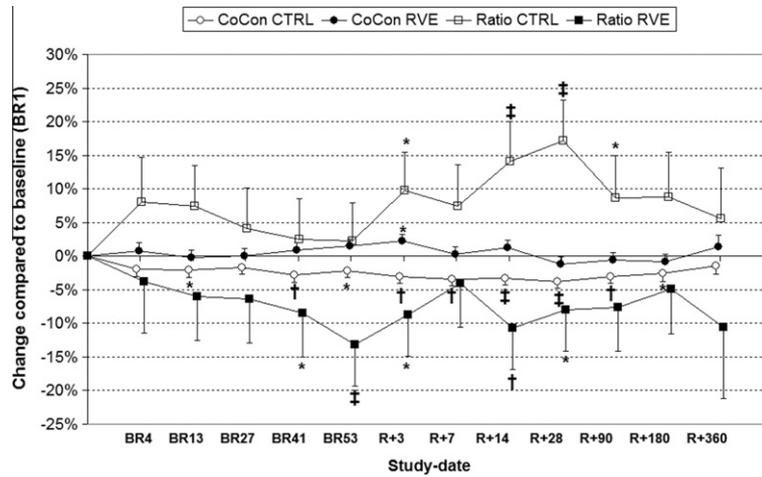


Fig. 2. Changes in lumbo-pelvic extensor-flexor co-contraction (*CoCon*) and activity-ratios (*Ratio*) over the course of the study. Values are mean(SEM) percentage difference to baseline (BR1) values. * $p < 0.05$; † $p < 0.01$; ‡ $p < 0.001$ and indicate significance of difference to baseline. BR = bed-rest, R+ = recovery. CTRL: inactive control group; RVE: resistive vibration exercise group. Group \times study-date effect on ANOVA reached significance for *Ratio* ($p = 0.011$), but not for *CoCon* ($p = 0.058$). Movement speed did not influence changes of *CoCon* over study-date ($p = 0.34$), and effects on *ratio* was similar across all muscles ($p \geq 0.59$) therefore results are pooled for muscle (*ratio* only) and movement speeds (*ratio* and *CoCon*). Some evidence ($p = 0.012$) was apparent from ANOVA for a different response of *ratio* between groups over time across movement speeds; see Fig. 3.

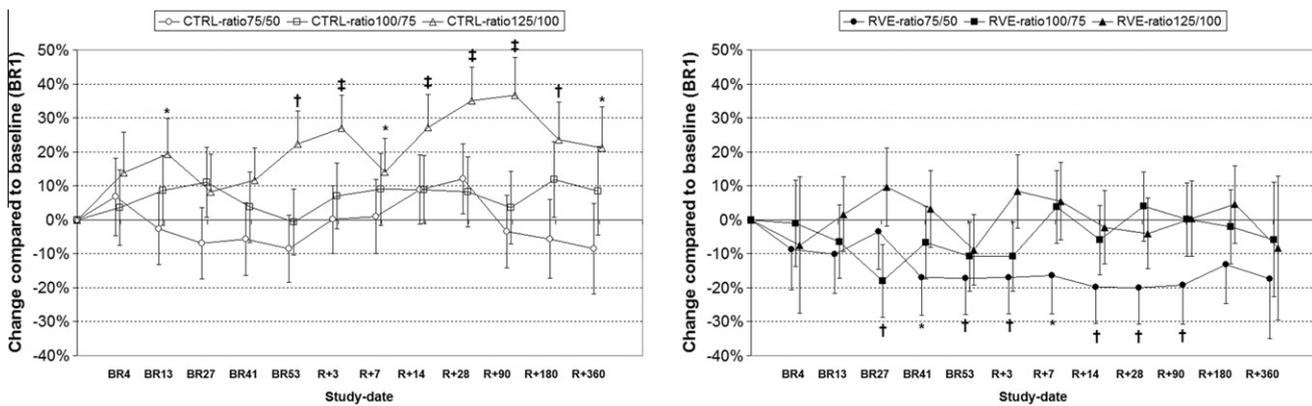


Fig. 3. Changes in activity-ratios (*ratio*) over the course of the study dependent upon movement speed. Values are mean(SEM) percentage difference to baseline (BR1) values. * $p < 0.05$; † $p < 0.01$; ‡ $p < 0.001$ and indicate significance of difference to baseline. BR = bed-rest, R+ = recovery. CTRL: inactive control group; RVE: resistive vibration exercise group. Data represent ratios of root-mean-square electromyographic amplitude between 75 and 50 cyc/min (*ratio*_{75/50}), 100 and 75 cyc/min (*ratio*_{100/75}) and 125 and 100 cyc/min (*ratio*_{125/100}) movement speeds. Effects on *ratio* were similar across all muscles ($p \geq 0.59$) therefore results are pooled across muscles. Analysis showed a difference in the response of the two subject groups over the course of the study dependent upon movement speed ($p = 0.012$), with the differences between the groups for *ratio*_{75/50} ($p = 0.0068$) and *ratio*_{125/100} ($p = 0.0036$) reaching significance (otherwise $p = 0.26$).

$p = 0.058$). No influence of movement speed on changes over time ($p = 0.34$) were seen for the *CoCon* variable.

Changes in amplitude-modulation (*BTR*) differed across muscles during the study (study-date \times muscle: $p = 0.0039$), with different response seen in the different groups (group \times study-date \times muscle: $p = 0.0126$) with no influence of movement speed in these effects ($p \geq 0.70$). Therefore the data presented in Fig. 4 have been pooled across movement speeds. The EO muscle showed no consistent pattern of change in either group (group \times study-date: $p = 0.11$). The IO muscle showed marginal increases of *BTR* in both groups, though there were no differences between the two groups (group \times study-date: $p = 0.43$). The LES muscles showed significant increases in *BTR* in the CTRL group, and whilst such increases were not seen in the RVE group, the difference between the two groups was not significant on ANOVA (group \times study-date: $p = 0.23$). *BTR* in the TES muscle group showed little significant change in the CTRL group, but increases seen in the RVE group, but there were no significant differences between the two groups on ANOVA (group \times study-date: $p = 0.55$). The IGM muscle showed non-

significant decreases in the CTRL group but significant increases in the RVE group with this effect being significant on ANOVA (group \times study-date: $p = 0.001$).

3.4. Trunk fat mass

Baseline mean(SEM) trunk fat mass was 7.15(1.20) kg in the CTRL group and 9.34(1.24) kg in the RVE group with no significant difference between the two groups at baseline ($p = 0.21$). Strongly significant increases in trunk fat mass were seen in the CTRL group during and after bed-rest (Fig. 5) with weaker increases in the RVE group. This effect was not significant on ANOVA, however (group \times study-date: $p = 0.19$). Correlations between baseline trunk fat mass (average of BDC-3 and BR2) and EMG (BR1) variables are shown in online Supplementary material. A consistent pattern of correlation was however not seen between trunk fat mass and the *BTR* or *ratio* variables and there was no association between trunk fat mass and *CoCon*.

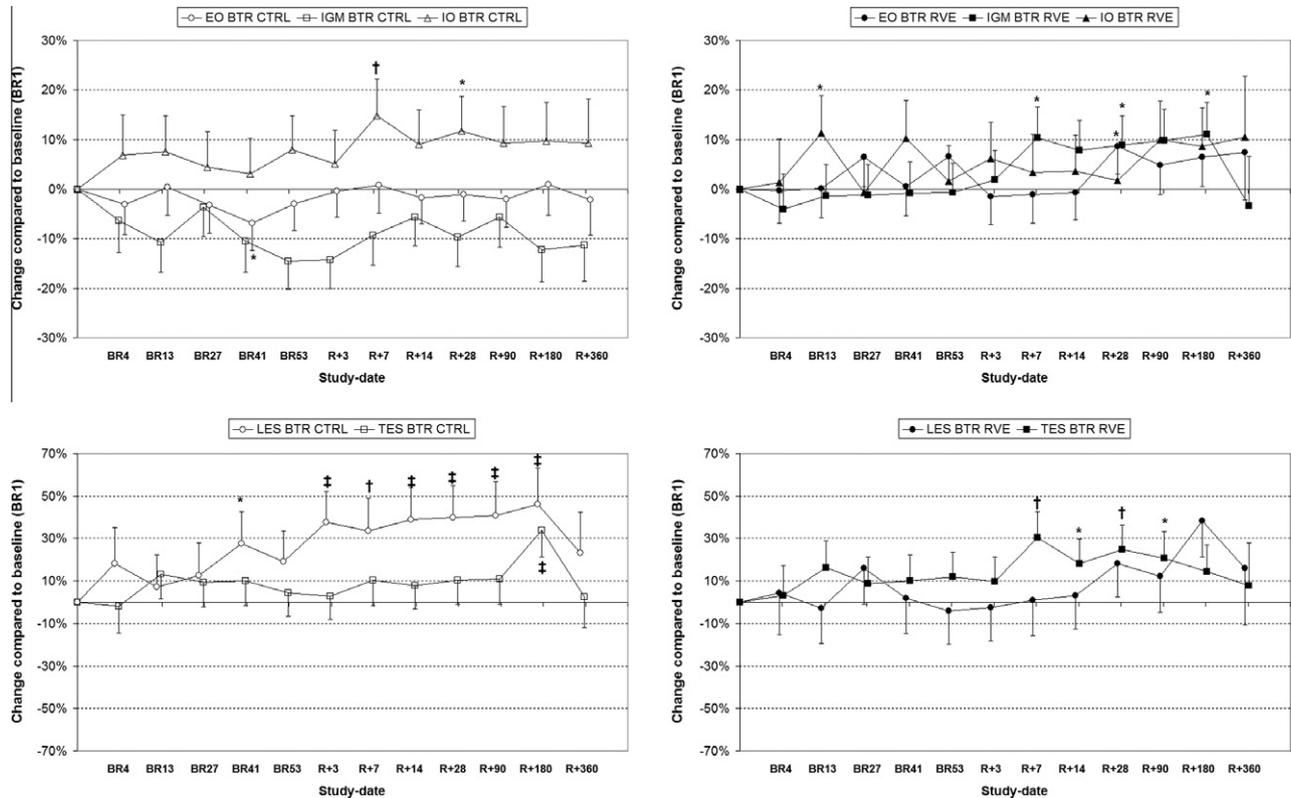


Fig. 4. Changes in tonic muscle activity (BTR) in the lumbo-pelvic musculature. Values are mean(SEM) percentage difference to baseline (BR1) values. * $p < 0.05$; † $p < 0.01$; ‡ $p < 0.001$ and indicate significance of difference to baseline. BR = bed-rest, R+ = recovery. CTRL: inactive control group (left); RVE: resistive vibration exercise group (right). EO: external oblique, IO: internal oblique, IGM: inferior gluteus maximus, TES: thoracic erector spinae, LES: lumbar erector spinae. Movement speed did not influence changes of each muscle over study-date ($p \geq 0.11$). Therefore results are averaged across movement speeds. ANOVA suggested a different response between groups over time for the different muscles (BTR: $p = 0.013$). Subsequent analyses for each muscle showed a significant group \times study-date interaction for BTR in IGM only ($p = 0.001$; otherwise $p \geq 0.113$).

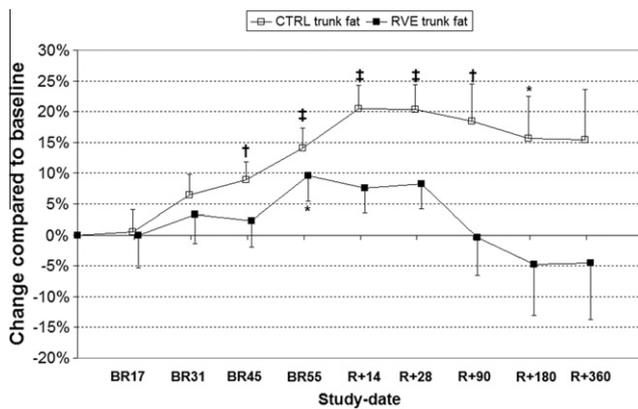


Fig. 5. Changes in trunk fat mass as measured by dual X-ray absorptiometry. Values are mean(SEM) percentage difference to baseline values. Baseline values were average of data collected 3-days prior to beginning of bed-rest (BDC-3) and on day-3 of bed-rest (BR2). * $p < 0.05$; † $p < 0.01$; ‡ $p < 0.001$ and indicate significance of difference to baseline. BR = bed-rest, R+ = recovery. CTRL: inactive control group; RVE: resistive vibration exercise group. Although the CTRL group showed stronger increases in trunk fat levels than the RVE group, this effect was not statistically significant on ANOVA (group \times study-date: $p = 0.19$).

4. Discussion

The current study examined the effect of a resistive vibration exercise (RVE) countermeasure on preventing motor control changes in the lumbo-pelvic musculature due to 56 days strict bed-rest. The loading of the spine during this exercise countermea-

sure occurred indirectly via shoulder straps. A number of differences were observed between the two subject groups, although not all were significant statistically on analysis of variance. These effects included an increase in activity-ratios (or "ramping" of electromyographic activation levels between movement speeds) in the inactive CTRL group but decreases in the RVE group which was significant on analysis of variance. Although the effects did not reach significance, the RVE group did not show the reductions of lumbo-pelvic extensor and flexor co-contraction seen in the CTRL group and the strong increase of lumbar erector spinae amplitude-modulation was not seen in the RVE group. Few changes were seen in the electromyographic signals from the thoracic erector spinae muscle group, with also little change of amplitude-modulation in the external oblique and internal oblique muscles. Prior publications (Belavý et al., 2010, 2007a,b) have considered the effects in the CTRL group in detail and thus the current discussion focuses on the impact of the exercise countermeasure using the CTRL group data as a reference only. The first step in understanding the true impact of the exercise countermeasure on lumbo-pelvic motor control during bed-rest is to determine which effects could be due to confounding factors, such as improvements in motor performance and alterations in subcutaneous fat levels.

As the subcutaneous fat layer increases in size, there is a greater low-pass filtering effect on the EMG signal and hence there is an alteration of the measured signal properties (de Luca, 1997). Since bed-rest typically results in changes in body composition (Blanc et al., 1998), we measured trunk fat mass using whole-body dual X-ray absorptiometry to examine whether this may represent a confounding factor for our results. Our results, similar to those of prior work (Hemingway et al., 1995; Nordander et al., 2003),

showed a negative correlation between trunk fat mass and electromyography activity-levels (online [Supplementary](#) material), but the relationships to other electromyography variables was less consistent. Hence, the effects seen in the amplitude-modulation, lumbo-pelvic extensor and flexor co-contraction and amplitude-ratio variables are unlikely to be due to increases in fat mass.

It is also possible that the improvements in movement performance seen over the course of the study contributed to the changes seen in motor control. In the partial-correlation analyses performed, little relationship could be found between movement accuracy and the electromyographic parameters. Although no clear relationship was seen, this of course does not rule out that skill acquisition may have played a role. Indeed, in considering a number of studies on changes in electromyographic parameters with skill acquisition, the relationship between skill improvement and motor control changes is not always clear. Different studies, often using different motor tasks, showed differing patterns of motor control adaptation with practice (Bernardi et al., 1996; Carson and Riek, 2001; Gabriel and Boucher, 1998; Gentili et al., 2006; Gribble et al., 2003; Ludwig, 1982), implying that the effect is highly dependent upon the task and muscle considered. Some authors also pointed out that motor control change with practice was often subject specific (Carson and Riek, 2001). Consequently, although we found no correlation between movement accuracy and the electromyographic parameters measured, it cannot be ruled out that skill improvement did not cause some of the changes seen in motor control, and a future longitudinal-study of skill acquisition with the current motor task would be required to resolve this issue. Nonetheless, the two subject groups in the current study showed similar improvements in motor skill over the course of the study. Hence, where the two groups showed opposing changes in motor control, it is likely these effects were due to an impact of the countermeasure, rather than practice.

In this vein, this leaves the effects on activity-ratios (increased in CTRL, decreased in RVE), lumbo-pelvic extensor and flexor co-contraction (decreased in CTRL, marginal increases in RVE) and amplitude-modulation in the lumbar erector spinae (greater increases in CTRL than RVE) as effects which could be attributed to the exercise countermeasure. Changes in trunk fat levels and movement accuracy cannot explain these findings and we consider that these effects were indeed due to a treatment effect of the RVE countermeasure. It should be stressed that the differences between groups in co-contraction represented a trend and the effect on lumbar erector spinae amplitude-modulation were not significant. The lumbar erector spinae muscle group showed the greatest number of changes in motor control due to bed-rest (Belavý et al., 2010, 2007a) and magnetic resonance imaging studies in the same subjects showed that this muscle group also showed the greatest amount of atrophy of the lumbo-pelvic muscles (Hides et al., 2007). The RVE countermeasure also reduced cross-sectional area loss of these short spinal extensors (Belavý et al., 2008). Thus, it is quite plausible that the amelioration of the motor control changes seen in the lumbar erector spinae muscle group was indeed a result of the countermeasure. It should be remembered that the movement task performed required the muscles of the lumbo-pelvic region to supply a “stable base” to permit efficient knee movement during the movement task. In light of this, given that the exercise countermeasure reduced losses in the “deeper” muscles of the lumbo-pelvic region (Belavý et al., 2008), it is our view that the increased “ramping” of superficial muscle activity-levels (as measured by amplitude-ratios) during the movement task was not necessary in the RVE group to stabilise the lumbo-pelvic region. The reduction of extensor–flexor co-contraction in the CTRL group could well be considered to be a reduction in motor

co-ordination at the lumbo-pelvic region (Belavý et al., 2007b), which was ameliorated (trend) by the RVE countermeasure.

Some of the findings from the inferior portion of the gluteus maximus muscle cannot be explained so readily. Significant increases of amplitude-modulation were seen for this muscle in the RVE group after bed-rest with little change in the CTRL group. Magnetic resonance imaging measurements (Grimaldi, 2008) of inferior gluteus maximus muscle cross-sectional area in the same subjects showed similar losses in both groups, on average 15.6%. It should be noted that in this magnetic resonance imaging study, only six subjects were measured in each group. Also, of the muscles measured, inferior portion of the gluteus maximus muscle was the most difficult from which to get strong electromyographic signal (due to the thick layer of overlying buttock-fat tissue). Further work would need to be performed to better understand the findings in this muscle.

It would be appropriate to discuss some of the mechanisms by which the RVE countermeasure may have reduced the motor control changes at the lumbo-pelvic region during and after bed-rest. On the one hand, the mechanical loading due to resistive exercise during exercise no doubt acted as a stimulus to maintain the musculature and also baseline neuromuscular function. However, whole-body vibration however can modulate lumbo-pelvic neuromuscular control, at least transiently (e.g. Fontana et al., 2005). Due to logistical and financial restrictions, the current study did not have an additional group with either only resistive exercise or only vibration exercise which would have helped to understand the effect of whole-body vibration alone. Hence, the reader should be cautioned against interpreting the findings of the current study on the RVE countermeasure as an effect of vibration *per se*: the countermeasure could have had an impact upon lumbo-pelvic muscle function via a number of physiological pathways.

The effects seen in the training group have some exercise prescription implications. Firstly, in terms of countermeasure exercise for spaceflight (simulation), effects on preventing motor control change at the lumbo-pelvic region can be achieved despite not including specific exercise manoeuvres for certain muscle groups (such as the extensors): in the current study indirect loading of the spine occurred via shoulder straps and the subjects needed to control their spinal position under this load. Whilst we argue that high-load resistive exercise is important for maintaining muscle mass in spaceflight (and simulation; see Belavý et al., 2009c for discussion), the maintenance of motor control and inter-muscular co-ordination appears to be more sensitive, even to lower loads. It should be noted however, that the subjects of the current study were young healthy men and caution is advised before applying such exercise protocols in patient populations (e.g. low back pain).

It is also important to mention some of the limitations of the current study. As in almost all studies in real or simulated micro-gravity the sample size in this study is also small, which may have prevented some effects from reaching statistical significance. The small number of subjects available for testing one-year after bed-rest may well have skewed the mean on this testing day. As already stressed, it is also important to note that further study should examine the effect of vibration alone or resistive exercise alone on the parameters measured here. Due to cost limitations in bed-rest studies, the Berlin Bed-Rest Study aimed first to evaluate the effectiveness of the countermeasure program as a whole with further studies to be planned should the countermeasure prove effective. As the current investigation was the first of its kind in prolonged bed-rest we unfortunately do not have access to prior data, or data on measurement repeatability, upon which to perform a sensitivity-analysis. Such a sensitivity-analysis would aid in the interpretation of non-significant findings. Also, future work

could consider whether additional benefits could be gained by other forms of exercise on preventing the effects of bed-rest on the parameters measured here. Additionally, it should be noted that some electromyographic parameters are related. Whilst the electromyographic parameters were designed to quantify different aspects of muscle function, there was some overlap between parameters. This effect was most obvious for root-mean-square electromyographic amplitude and amplitude-modulation where the partial-correlation analyses (online [Supplementary material](#)) showed a weak to moderate correlation between these two variables at baseline and the changes over time in these two parameters largely paralleled one another. For the remaining electromyographic parameters, however, the correlations between them were quite weak, indicating that they do indeed measure different aspects of motor control.

In conclusion, the current study examined the effect of a resistive vibration exercise (RVE) countermeasure on preventing motor control changes in the lumbo-pelvic musculature due to 56 days strict bed-rest. After considering the potential confounding influences of increases in trunk fat levels and improvements in motor skill, we found a significant impact of the RVE intervention in ameliorating the generalised increases in activity-ratios of the lumbo-pelvic musculature seen in bed-rest. Furthermore, the RVE group showed marginal increases lumbo-pelvic extensor and flexor co-contraction whereas this reduced significantly in the CTRL group, although this between-group effect was trend and did not reach significance. Also, although the between-group effects were not statistically significant, the RVE group also did not show the increases in amplitude-modulation of the lumbar erector spinae that were observed in the CTRL group. These results showed that the RVE countermeasure as implemented was capable of ameliorating some, but not all, changes of motor control in the lumbo-pelvic region as a result of prolonged bed-rest.

Conflict of interest statement

The authors have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jelekin.2011.09.009](https://doi.org/10.1016/j.jelekin.2011.09.009).

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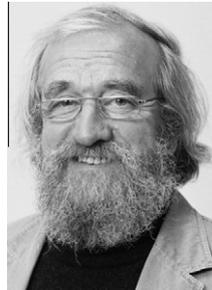
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Table 1: Baseline (BR1) movement accuracy

Movement-speed	Movement accuracy variables					
	MSE_{0°	MSE_{45°	MSE_{speed}	$All-MSE_{0^\circ}$	$All-MSE_{45^\circ}$	$All-MSE_{\text{speed}}$
<i>Inactive control group (CTRL)</i>						
50 cyc/min	0.81(0.41)	1.78(0.23)	6.39(0.83)	0.77(0.23)	2.06(0.67)	10.81(2.43)
75 cyc/min	1.21(0.43)	1.52(0.22)	6.75(0.71)	1.32(0.27)	2.82(0.69)	21.88(5.17)*
100 cyc/min	1.94(0.43)*	2.37(0.25)	6.38(0.69)	2.13(0.34)‡	3.66(0.77)	26.46(6.20)*
125 cyc/min	3.80(0.50)‡	3.20(0.31)‡	7.28(0.85)	4.38(0.47)‡	6.06(0.90)‡	83.47(18.84)‡
<i>Resistive vibration exercise group (RVE)</i>						
50 cyc/min	1.54(0.31)	2.16(0.30)	4.03(0.58)	1.59(0.34)	2.91(0.51)	6.86(1.49)
75 cyc/min	1.16(0.31)	2.77(0.32)	6.82(0.72)	1.44(0.34)	4.33(0.73)	13.57(2.77)*
100 cyc/min	2.54(0.37)*	3.39(0.32)*	6.16(0.65)	2.95(0.48)*	5.31(0.54)‡	20.57(3.56)†
125 cyc/min	2.30(0.44)	3.98(0.36)†	7.40(1.11)	3.76(0.67)†	7.69(0.96)‡	93.93(18.23)‡

5 Values are mean(SEM). MSE_{0° and MSE_{45° variables are in degrees MSE_{speed} variables are in cycles per minute. *: $p < 0.05$; †: $p < 0.01$; ‡: $p < 0.001$ and indicates significance of difference to value at 50 cyc/min. MSE_{45° was higher at baseline in the RVE group ($p < 0.001$), otherwise there were no differences between the groups at baseline ($p \geq 0.053$). MSE_{0° and MSE_{45° and MSE_{speed} are mean-squared error around their respective extension position, flexion position and speed target targets within the sections of the goniometer trace which were defined as “acceptable” for further analysis of

10 EMG data (see *Methods*). $All-MSE_{0^\circ}$ and $All-MSE_{45^\circ}$ and $All-MSE_{\text{speed}}$ represent mean-squared error of entire goniometer trace around their respective targets from each movement trial. $All-MSE$ variables were used to track changes in movement performance over the course of the study (see supplementary online material Figure 2), whereas the MSE variables were generated solely to correlate with the corresponding EMG variables at baseline (see supplementary online material Table

15 3).

Table 2: Baseline (BR1) electromyographic parameters

Movement-speed (cyc/min)	RMS (mV)		PHZ (degrees)	
	CTRL	RVE	CTRL	RVE
<i>External Oblique</i>				
50 cyc/min	5.40(1.16)	4.76(0.60)	164.24(121.14)	103.41(119.17)
75 cyc/min	6.80(1.47)*	5.77(0.74)	-91.22(88.76)	-27.60(30.99)
100 cyc/min	11.55(2.51)‡	8.37(1.08)†	-79.77(78.28)	-77.51(70.07)
125 cyc/min	19.23(4.29)‡	15.21(2.37)‡	-75.85(74.76)	-47.46(47.05)
<i>Inferior Gluteus Maximus</i>				
50 cyc/min	1.43(0.21)	1.22(0.08)	150.63(148.41)	#DIV/0!
75 cyc/min	1.98(0.29)	1.54(0.11)*	131.21(133.05)	92.96(94.17)
100 cyc/min	3.46(0.51)‡	2.29(0.16)‡	128.44(130.68)	117.35(116.89)
125 cyc/min	6.52(1.04)‡	4.14(0.36)‡	138.51(139.33)	133.23(131.99)
<i>Internal Oblique</i>				
50 cyc/min	7.77(1.17)	3.41(0.43)	-177.45(93.61)	80.77(87.61)
75 cyc/min	12.88(1.94)*	5.53(0.72)†	126.47(125.25)	-43.13(76.64)
100 cyc/min	23.36(3.52)‡	9.48(1.23)‡	-97.68(86.19)	-20.35(58.53)
125 cyc/min	34.41(5.60)‡	14.76(2.22)‡	-98.97(88.85)	-61.45(70.41)
<i>Lumbar Erector Spinae</i>				
50 cyc/min	2.99(1.07)	1.88(0.30)	171.76(156.74)	144.37(143.44)
75 cyc/min	6.76(2.41)†	7.55(1.22)‡	118.40(122.17)	122.89(122.89)
100 cyc/min	13.89(4.96)‡	20.78(3.23)‡	122.11(124.98)	127.25(127.20)
125 cyc/min	21.48(7.88)‡	33.09(5.86)‡	133.37(134.71)	134.05(133.91)

Thoracic Erector Spinae

50 cyc/min	3.84(0.68)	2.95(0.42)	-90.00(79.24)	-25.43(26.29)
75 cyc/min	4.90(0.87)	3.81(0.55)	-131.71(99.09)	104.86(112.74)
100 cyc/min	7.41(1.32)‡	8.79(1.29)‡	166.21(130.95)	131.06(131.57)
125 cyc/min	11.87(2.24)‡	15.97(2.76)‡	159.61(129.01)	131.76(132.52)

5 Values are mean(SEM) root-mean-square (*RMS*) EMG amplitude and activation timing (phase-lead/lag, *PHZ*; or where EMG peaks occur relative to peaks in EMG signal). Activation time (*PHZ*) could not be measured for all muscles at all measurement speeds as sufficient amplitude modulation of the EMG signal must be present in order to detect a phase-lead/lag of the EMG trace relative to the goniometer trace (“-” indicates missing data). These *PHZ* data are from 100 Hz high-pass filter. Internal oblique *RMS* ($p=0.007$) was higher on average in the CTRL group at baseline with the LES-RMS showing a different response with movement-speed in the two groups at baseline ($p=0.037$). Otherwise there were no significant differences between the groups at baseline ($p \geq 0.074$).

Table 3: Correlations between movement accuracy and electromyographic parameters at baseline (BR1)

Parameter	MSE_{0°	MSE_{45°	MSE_{speed}	RMS	CoCon	BTR	ratio
MSE_{0°		-0.01	-0.15	-0.09	0.16	0.01	-0.08
MSE_{45°	0.41		0.33	0.1	0.01	0.13	0.08
MSE_{speed}	0.11	0.27		-0.04	-0.21	0.09	0.04
RMS	0.25	0.27	0.12		-0.02	0.37	0.21
CoCon	-0.34	-0.41	-0.22	-0.34		-0.27	-0.1
BTR	0.2	0.28	0.12	0.52	-0.39		0.22
ratio	0.01	0.13	0.09	0.25	-0.25	0.29	

5 Values are Pearson's correlation co-efficient. Values in bottom left (grey background) triangle are correlations between parameters for all muscles and movement-speeds. Values in top right triangle are Pearson's partial correlation co-efficients controlling for movement-speed and muscle. Correlations are for descriptive purposes only and hence testing of statistical significance was not performed. Correlations with activation timing (*PHZ*) variable could not be performed as this is a circular variable. Note that movement accuracy variables (MSE_{0° , MSE_{45° , MSE_{speed}) are not correlated with EMG variables once confounding factors (such as movement-speed) are controlled for.

10

Table 4: Correlations between trunk fat mass and electromyographic variables at baseline (BR1)

Muscle	RMS	<i>CoCon</i>	<i>BTR</i>	<i>ratio</i>
External Oblique	-0.14	-	-0.27	0.19
Internal Oblique	-0.33	-	0.02	-0.07
Inferior Gluteus Maximus	-0.25	-	-0.09	-0.16
Lumbar Erector Spinae	-0.08	-	-0.16	-0.11
Thoracic Erector Spinae	-0.06	-	0.15	0.32
All muscles pooled	-0.28	0.05	-0.17	-0.04

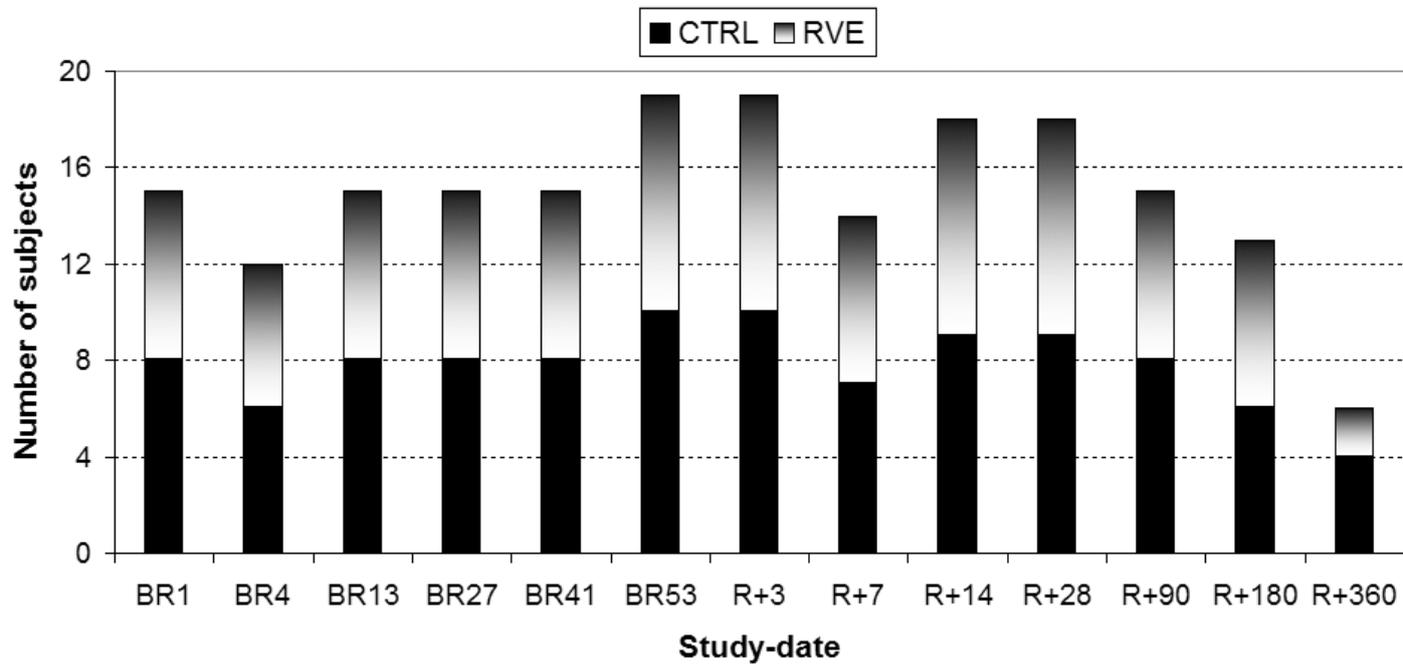
5 Values are Pearson's correlation co-efficient. EMG variables were averaged across speeds within each subject and muscle prior to comparison to trunk fat mass. For "all muscles pooled", values were averaged within each subject across all muscles. Correlations are for descriptive purposes only and hence testing of statistical significance was not performed. Correlations with activation timing (*PHZ*) variable could not be performed as this is a circular variable. Note that root-mean-square (RMS) EMG amplitude is consistently negatively
10 correlated with fat mass (i.e. increases in fat mass are associated with lower activity levels). EMG amplitude modulation (*BTR*) and activity ratios (*ratio*) do not however show this consistent pattern and the extent of lumbo-pelvic extensor and flexor co-contraction (*CoCon*) appears unrelated to trunk fat mass.

Table 5: Activation timing (phase-lead/lag; PHZ) over the course of the study

Group	Study-date												
	BR1	BR4	BR13	BR27	BR41	BR53	R+3	R+7	R+14	R+28	R+90	R+180	R+360
100 Hz high pass filter prior to further processing													
<i>External Oblique</i>													
CTRL	-85(-35, -105)	-86(-53, 23)	-81(-46, 21)	-82(-52, 22)	-91(-17, 47)	-91(-16, 45)	-87(-44, 20)	-109(-17, 49)	-104(-17, 48)	-120(-18, 52)	-73(-50, 21)	-136(-17, 53)	-69(-61, 23)
RVE	-49(0, -88)	-83(121, 48)*	-106(1, 293)*	-64(-46, 41)	-97(0, 171)	-125(1, -13)	178(44, 307)*	-169(0, 182)*	152(42, 311)*	-114(0, 4)	-104(0, 182)*	-96(-1, 108)	-116(-111, -21)
<i>Inferior Gluteus Maximus</i>													
CTRL	131(151, 112)	127(-18, 17)	133(-18, 17)	137(-17, 16)	135(-18, 17)	134(-16, 15)	139(-15, 14)	139(-17, 16)	130(-15, 14)	132(-16, 15)	128(-17, 16)	140(-19, 17)	124(-20, 16)
RVE	122(140, 105)	127(-20, 16)	120(-16, 14)	127(-16, 14)	121(-15, 13)	122(-14, 13)	119(-14, 13)	120(-15, 13)	116(-14, 13)	111(-14, 12)	118(-15, 13)	110(-14, 13)	101(-20, 16)
<i>Internal Oblique</i>													
CTRL	-97(-62, 153)	-180(-36, 102)	-118(-36, 98)	-120(-35, 97)	-143(-36, 98)	-174(-35, 95)	-175(-35, 94)	-173(-35, 97)	-140(-36, 96)	-161(-35, 95)	168(25, 244)*	95(26, 243)*	151(28, 174)
RVE	67(110, -16)	174(-130, 14)	131(-121, 14)	122(-125, 13)	78(-42, 68)	108(-122, 14)	77(-42, 68)	89(-43, 70)	116(-125, 14)	98(-120, 13)	93(-123, 14)	127(-126, 14)	155(-14, 112)
<i>Lumbar Erector Spinae</i>													
CTRL	133(152, 116)	140(-15, 14)	150(-14, 12)	144(-14, 13)	149(-13, 12)	147(-13, 12)	141(-13, 12)	142(-14, 12)	138(-13, 12)	137(-13, 12)	131(-14, 12)	130(-15, 13)	125(-16, 14)
RVE	133(151, 118)	138(-14, 13)	142(-13, 12)	145(-12, 11)	144(-12, 11)	143(-12, 11)	140(-12, 11)	137(-12, 11)	131(-12, 11)	133(-12, 11)	134(-12, 11)	131(-13, 12)	135(-14, 13)
<i>Thoracic Erector Spinae</i>													
CTRL	163(-159, 112)	141(-39, 59)	147(-34, 51)	161(-34, 52)	149(-35, 51)	176(-33, 49)	171(-34, 50)	172(-34, 50)	148(-34, 50)	165(-34, 50)	147(-35, 52)	122(-36, 53)	150(-37, 54)
RVE	128(159, 105)	133(-34, 27)	133(-28, 23)	139(-29, 23)	144(-29, 23)	139(-27, 22)	142(-29, 23)	131(-29, 23)	136(-28, 22)	135(-28, 22)	119(-28, 23)	125(-29, 24)	138(-40, 28)
20 Hz high pass filter prior to further processing													
<i>External Oblique</i>													
CTRL	-46(-14, -76)	-56(-43, 40)	-50(-31, 30)	-45(-32, 32)	-61(-32, 33)	-56(-30, 30)	-51(-30, 30)	-53(-30, 30)	-35(-30, 29)	-55(-30, 30)	-57(-30, 29)	-66(-31, 31)	-62(-32, 32)
RVE	-52(-8, -87)	-26(-49, 41)	-56(-43, 37)	-41(-44, 36)	-66(-44, 38)	-73(-43, 36)	-75(-43, 36)	-33(-43, 37)	-58(-42, 36)	-62(-41, 34)	-48(-44, 37)	-59(-42, 35)	-40(28, 72)
<i>Inferior Gluteus Maximus</i>													
CTRL	115(138, 94)	111(-23, 20)	123(-21, 19)	134(-21, 19)	133(-24, 19)	120(-21, 19)	120(-21, 19)	129(-23, 20)	127(-23, 20)	131(-24, 21)	122(-23, 21)	115(-27, 23)	126(-30, 24)
RVE	119(140, 98)	115(-27, 23)	113(-19, 19)	113(-20, 19)	111(-20, 19)	117(-19, 18)	130(-20, 18)	116(-19, 18)	116(-18, 18)	110(-18, 17)	117(-19, 18)	110(-18, 17)	96(-30, 24)
<i>Internal Oblique</i>													
CTRL	172(-135, 58)	-125(-198, -27)*	51(29, 219)*	-93(-130, 39)	-86(57, -18)	-58(58, 38)*	-70(57, 14)*	-122(-186, -17)*	-59(58, 35)*	-84(58, -15)	-165(-273, -103)*	59(30, 220)*	159(-45, 115)
RVE	46(87, -4)	154(-22, 2)	47(-39, 37)	58(-40, 39)	61(-38, 36)	77(-38, 36)	62(-37, 35)	65(-38, 36)	91(-25, 2)	53(-43, 41)	96(-24, 2)	79(-42, 39)	88(-58, 14)
<i>Lumbar Erector Spinae</i>													
CTRL	126(145, 110)	138(-17, 15)	145(-16, 15)	145(-15, 14)	149(-15, 13)	151(-14, 13)	144(-14, 13)	143(-15, 14)	137(-14, 13)	136(-15, 13)	133(-15, 14)	137(-17, 15)	131(-18, 16)
RVE	135(151, 120)	143(-14, 14)	142(-14, 14)	147(-13, 12)	142(-13, 13)	150(-12, 12)	143(-12, 12)	140(-13, 13)	136(-12, 12)	135(-12, 12)	132(-13, 13)	137(-13, 13)	125(-16, 14)
<i>Thoracic Erector Spinae</i>													
CTRL	-161(-94, 163)	160(-15, 118)	162(-14, 107)	162(-14, 101)	168(-15, 102)	-174(-66, 35)	179(-14, 99)	167(-14, 102)	154(-14, 98)	161(-14, 103)	168(-14, 103)	110(-14, 105)	149(-15, 101)
RVE	148(174, 117)	150(-28, 35)	147(-26, 33)	157(-28, 33)	145(-26, 32)	156(-24, 29)	158(-24, 30)	141(-24, 30)	135(-24, 29)	140(-23, 29)	131(-25, 30)	142(-25, 31)	126(-30, 24)

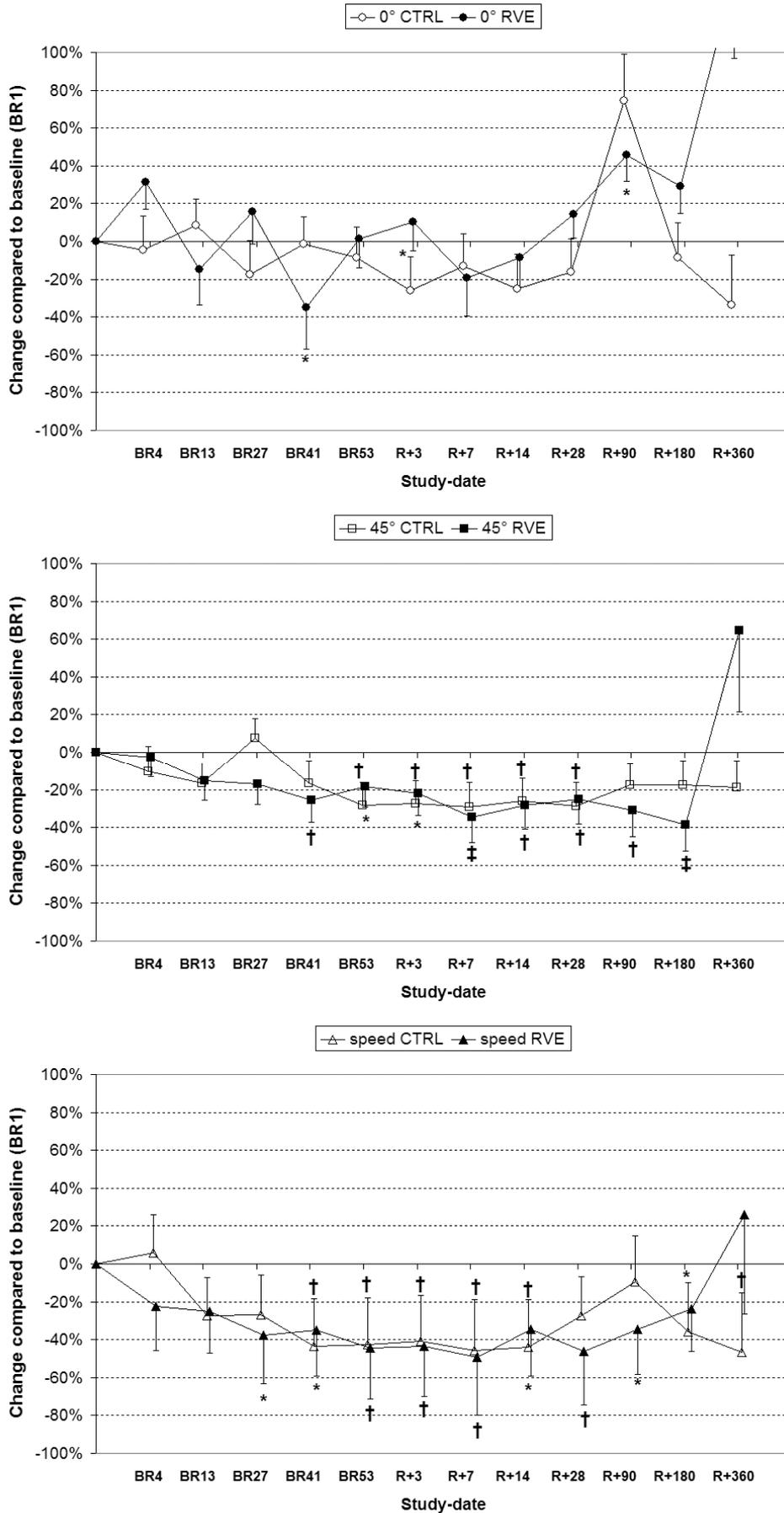
Values are mean phase-lead/lad on each study-date in degrees. Values in brackets are 95% confidence interval of mean change compared to baseline: if the confidence interval does not cross zero, then the difference to baseline is “significant” at $p < 0.05$. BR=bed-rest, R+=recovery. CTRL: inactive control group; RVE: resistive vibration exercise group. Two versions of the data have been presented: one using a 100Hz high-pass filter prior to further signal processing and another using a 20Hz high-pass filter (the latter used in prior work; Belavý et al, 2010). The 100Hz high-pass filter is more effective in removing cardiac signals from the EMG trace which were often present in the external oblique, internal oblique and thoracic erector spinae signals.

Figure 1: Number of datasets available for analysis



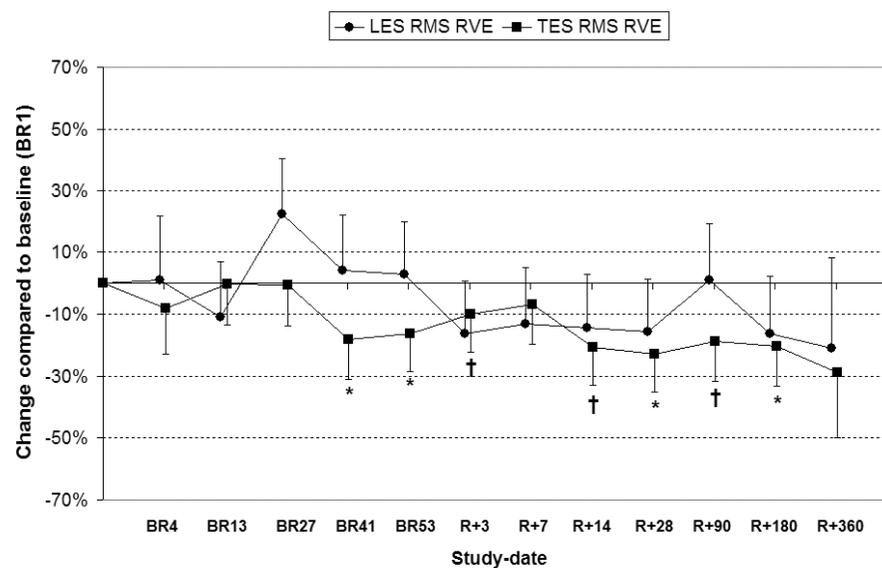
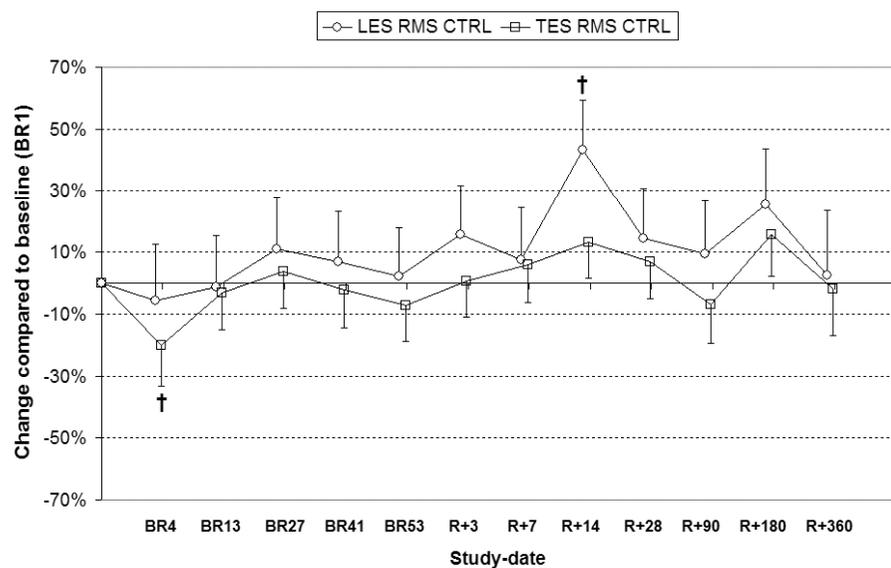
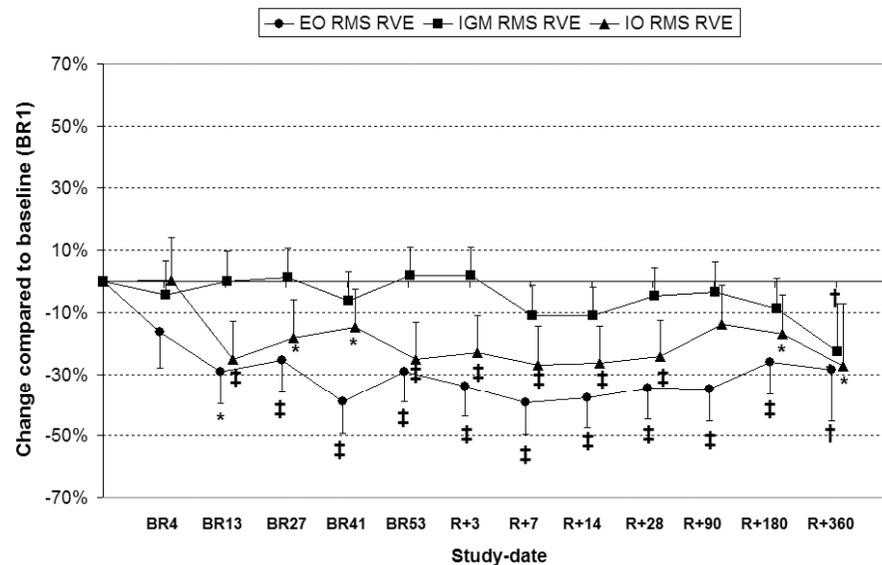
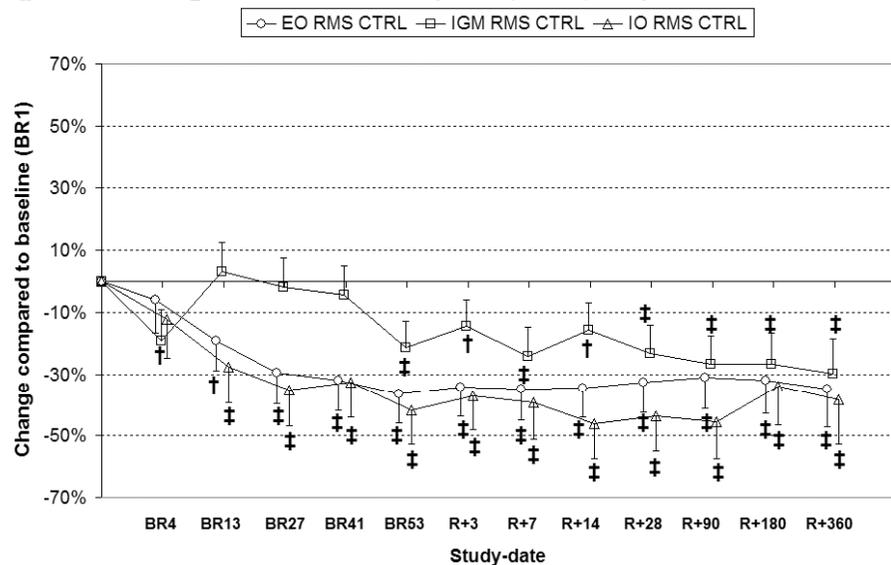
5 Due to subject absence and or technical issues, datasets were not available from all subjects on all measurement dates. CTRL: inactive control group; RVE: resistive vibration exercise group.

Figure 2: Improvements in movement performance over the course of the study.



5 Values are mean(SEM) percentage difference to baseline (BR1) values. Data refer to mean-squared error (MSE) around targets from entire goniometer trace for extension (*All-MSE*_{0°}; top), flexion (*All-MSE*_{45°}; middle) and movement-speed (*All-MSE*_{speed}; bottom). RVE-group R+360 *All-MSE*_{0°} value was 141.3(44.3)%. See Table 1 for baseline (BR1) values. *: $p < 0.05$; †: $p < 0.01$; ‡: $p < 0.001$ and indicate significance of difference to baseline. BR=bed-rest, R+=recovery. CTRL: inactive control group; RVE: resistive vibration exercise group. With the exception of *All-MSE*_{0°} ($p=0.005$; see text), movement-speed was unrelated to the differences between groups over the course of the study. Neither *All-MSE*_{45°} ($p=0.09$) nor *All-MSE*_{speed} ($p=0.51$) showed any between group differences.

Figure 3: Changes in root-mean-square (RMS) amplitude in the lumbo-pelvic musculature



Values are mean(SEM) percentage difference to baseline (BR1) values. *: $p < 0.05$; †: $p < 0.01$; ‡: $p < 0.001$ and indicate significance of difference to baseline. BR=bed-rest, R+=recovery. CTRL: inactive control group (left); RVE: resistive vibration exercise group (right). EO: external oblique, IO: internal oblique, IGM: inferior gluteus maximus, TES: thoracic erector spinae, LES: lumbar erector spinae. Movement speed did not influence changes of each muscle over study-date ($p \geq 0.11$), therefore results are averaged across movement speeds. ANOVA suggested a different response between groups over time for the different muscles (RMS: $p < 0.001$). Subsequent analyses for each muscle showed a significant group×study-date interaction for RMS for IO, IGM, LES and TES ($p \leq 0.018$; EO $p = 0.26$).